Large scale deformations of the western U.S. Cordillera: Collaborative research with Smithsonian Astrophysical Observatory and California Institute of Technology

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Program Element I

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INTRODUCTION

Destructive earthquakes occur throughout the western U.S. Cordillera (WUSC), not just within the San Andreas fault zone. But because we do not understand the present-day large-scale deformations of the crust throughout the WUSC, our ability to assess the potential for seismic hazards in this region remains severely limited. To address this problem, we are using a large collection of Global Positioning System (GPS) networks which spans the WUSC to precisely quantify present-day large-scale crustal deformations in a single uniform reference frame. Our work can roughly be divided into an analysis of the GPS observations to infer the deformation field across and within the entire plate boundary zone and an investigation of the implications of this deformation field regarding plate boundary dynamics.

INVESTIGATIONS

We have used data from continuous and campaign GPS, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and DORIS geodetic networks (see http://cfa-www.harvard.edu/space_geodesy/WUSC/) throughout the WUSC and the world. We chose to work with these particular geodetic networks because (1) as space geodetic networks, they provide vector measurements with respect to an external reference frame, (2) data products necessary to estimate precise velocities for these networks were readily available, and (3) these networks provide fairly uniform coverage of the western United States.

Estimation of a uniform set of station velocities from a vast amount of space geodetic data from different techniques requires methods for (1) reducing an enormous number of raw geodetic observations to geodetic parameter estimates such as site positions and velocities, Earth orientation parameters, satellite orbital parameters, and radio source locations, and (2) combining the results to form a self consistent set of site velocities in a uniform reference frame.

The basic approach that we take is to analyze the data in subnetworks, and then subsequently combine the subnetwork solutions using procedures analogous to sequential least squares. One of the main advantages of this "distributed processing" strategy is that it allows for subsets of stations to be analyzed in parallel. An important feature of the particular approach to distributed processing that we have adopted is that the reference frame is not defined until the very last step in the analyses. This is achieved by applying loose constraints when reducing the raw data such that reference frame indeterminacy is regularized, but without affecting the invariant properties of the parameter estimates [e.g., Herring et al., 1991; Heflin et al., 1992]. Hence, different analysts can share data products without having to worry about the particular values the other analysts have adopted to define their reference frames.

Our data analyses can be divided into five main steps (Figure 1). The first step, which involved reduction of the raw space geodetic data, was largely performed by others, including SOPAC, SCEC, and Goddard Space Flight Center, and LAREG. The raw GPS data, for example, were analyzed at Scripps Orbit and Permanent Array Center (SOPAC), the Southern California Earthquake Center(SCEC), and the Harvard-Smithsonian Center for Astrophysics. The basic products of this first step were nominally, for each network/subnetwork, sets of one-day site-position estimates, Earth orientation parameters, and associated error covariance matrices. These data products are stored in SINEX (Software INdependent EXchange) format [cf. ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex.txt] or equivalent files.

The second step in our analyses applies only to the GPS data sets. Once the GPS parameter estimates were obtained from the raw data for the different subnetworks, they were combined using the GLOBK software [Herring, 1999] to form total network solutions. A more detailed description of the mathematics involved in data combination and specific implementation in the GLOBK software can be found in Dong et al. [1998] and Herring [1999].

In the third step, we used the GLOBK software to estimate GPS and VLBI site velocities from all available solution files. For GPS, we used the total network and campaign combinations obtained in step two. For VLBI, we used the SINEX files provided by Goddard Space Flight Center (GSFC). SINEX files for SLR and DORIS networks, available from Laboratoire de Recherche en Geodesie (LAREG) already contain site velocities, therefore we did not need to go back to the site position data for these networks. We estimated site velocities for the GPS and VLBI networks separately. We excluded from our solution all site-position data whose evolution was obviously not well described by a constant velocity, except that we allowed for discrete offsets due to earthquakes, antenna changes, etc.

In the fourth step, we combined the resulting velocity estimates derived from the different techniques to estimate a single set of site velocities for all stations in all networks. We used the GLOBK analysis software to determine these velocity estimates, accounting for the fact that the reference frames implicit to the velocity estimate sets used as input depend in a complicated way on numerous factors, including the locations of the particular stations in each set. This velocity combination is similar to that of the data combination described in step two above, except that in this step the velocities of the stations are being adjusted to form a uniform time dependent reference frame rather than a static reference frame for the positions of the stations at a single epoch. We made no attempt to constrain the relative positions of collocated or nearly collocated stations. Instead, the velocity estimates of stations located within 1km of one another were constrained to be equal, effectively tying the velocities of all antennas located at the same site. Consequently, after step four, some velocities reflect data from more than one station, possibly from more than one space geodetic technique.

In the fifth step, we rotated the velocity field from the global geodetic reference frame implicit to the velocity estimates obtained in step four into a North America-fixed reference frame. We realized this reference frame by estimating via a weighted-least squares analysis that rigid rotation which minimized the velocities of 59 sites assumed to define a stable North America plate interior, including sites on the Colorado Plateau. We then subtracted the contribution of this rotation from the velocities of all of the stations in the network. The resulting horizontal components of the velocities in this reference frame for sites in the western United States are shown in Figure 2.

RESULTS

We have used the WUSC velocity field to investigate the distribution of extension and shear in the northern Basin and Range province and the kinematics of the Pacific-North America plate boundary zone. To understand the contemporary strain field in the northern Basin and Range province in the context of the greater Pacific-North America plate boundary zone, we estimated the relative motions of the Colorado Plateau, the Sierra Nevada-Great Valley microplate, and a reference line just east of the Walker Lane Belt in the Great Basin. We estimate relative motion between the Sierra Nevada-Great Valley microplate and the Colorado Plateau of 11.7+-0.1 mm/yr oriented N40W. We estimate that the eastern Great Basin accommodates a total motion of 3.3+-0.1 mm/yr oriented N77W. The difference between these vector boundary conditions provides us with an estimate for the total deformation across the Walker Lane Belt of 9.3+-0.1mm/yr oriented N28W. This deformation is accommodated across a region of width ~150 km at the latitude of Death Valley with right lateral shear strain rates in excess of 50 nstr/yr. The shear zone widens to ~300 km to the north accommodating shear strain at rates of around 25 nstr/yr. We observe no appreciable extension perpendicular to the shear zone in either of these regions. However, we observe about 7 nstr/yr extension in the direction of shear from southeast to northwest, comparable to the northern Basin and Range average extension rate of about 10 nstr/yr, but implying a distinctly different mechanism of deformation from east-west extension on north-trending range bounding normal faults. We also observe an intriguing oscillatory spatial pattern in the deformation field of amplitude ~2 mm/yr within the shear zone at the latitude of Death Valley. Possible sources of this anomalous deformation pattern include post-seismic relaxation associated with the 1872 Owen's Valley earthquake, delamination of a crustal root beneath the southern Sierra Nevada, or perhaps competition between plate boundary shear and buoyancy forces in the lithosphere.

NON-TECHNICAL SUMMARY

Destructive earthquakes occur throughout the WUSC, not just within the San Andreas fault zone. But because we do not understand the present-day large-scale deformations of the crust within this region (extending from the Pacific coast to the Wasatch Front), our ability to assess the potential for seismic hazards remains severely limited. GPS geodesy is the only practical method for determining detailed crustal deformation at this scale. GPS networks now cover many sub-regions within the WUSC. These networks do not, however, provide a single, coherent picture of the present-day crustal deformation field if treated independently; biases which inevitably affect each realization of the geodetic reference frame are significant relative to the expected low velocities. We are addressing this problem by combining geodetic data products derived independently from these small scale networks, which are already widely available, using a technique specifically designed to render these reference frame errors negligible. We are determining, for the first time, a coherent crustal velocity field for the entire WUSC. We are using the new velocity results to understand the kinematics of deformation and to determine parameters (e.g., fault slip rates, strain rates) for models appropriate to particular regimes of deformation within the WUSC that we have identified.

DISSEMINATION

With in-kind support from the Atherton Seidell Grant Program of the Smithsonian Institution, we have built a data dissemination system that allows users to manipulate and download our combined WUSC velocity solution using the World-Wide-Web. The URL for the web site is <http://cfa-www.harvard.edu/space_geodesy/WUSC/>.

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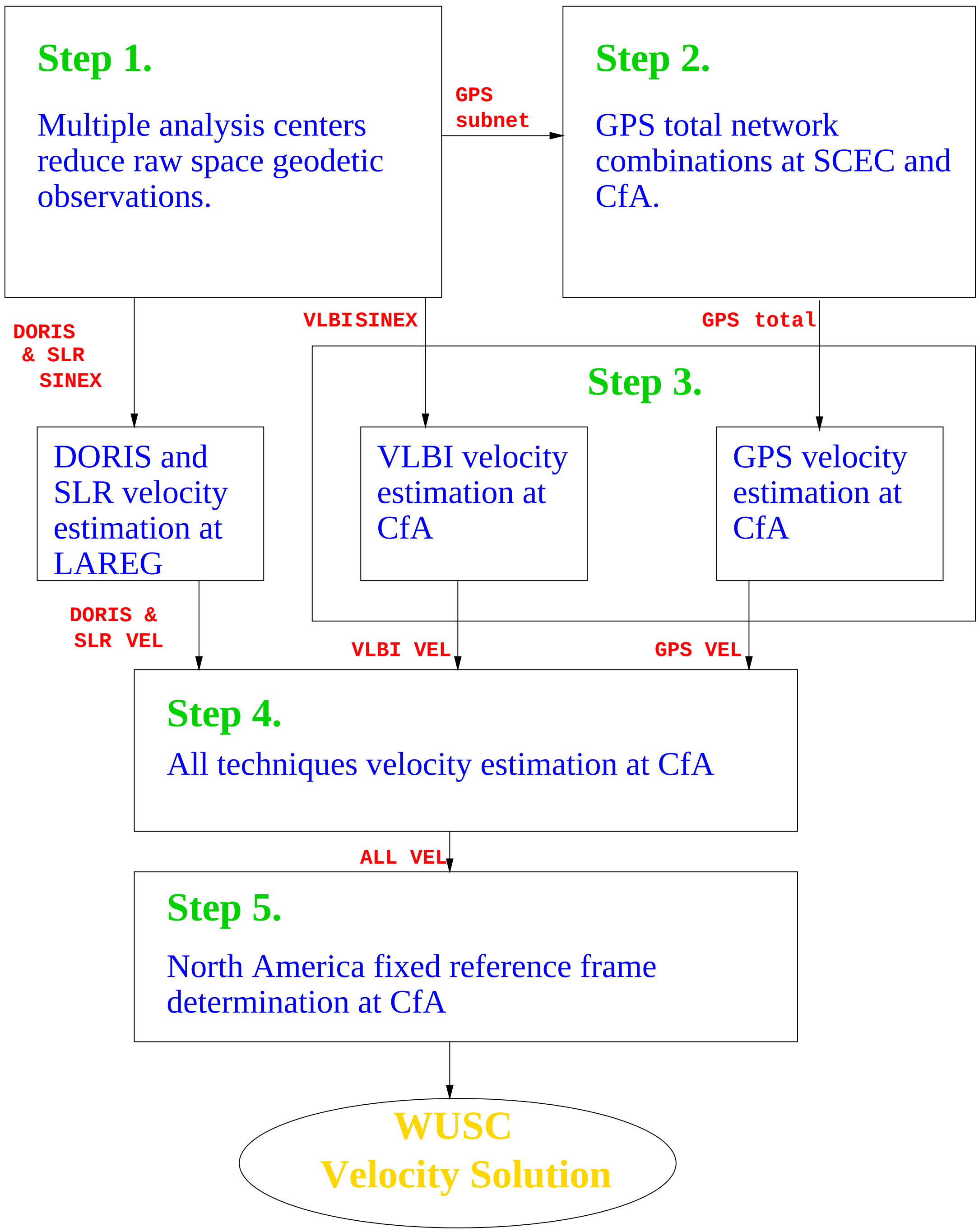

Figure 1 Five step distributed data analysis procedure. CfA = Harvard-Smithsonian Center for Astrophysics. SCEC = Southern California Earthquake Center. LAREG = Laboratoire de Recherche en Geodesie. WUSC = Western U.S. Cordillera.

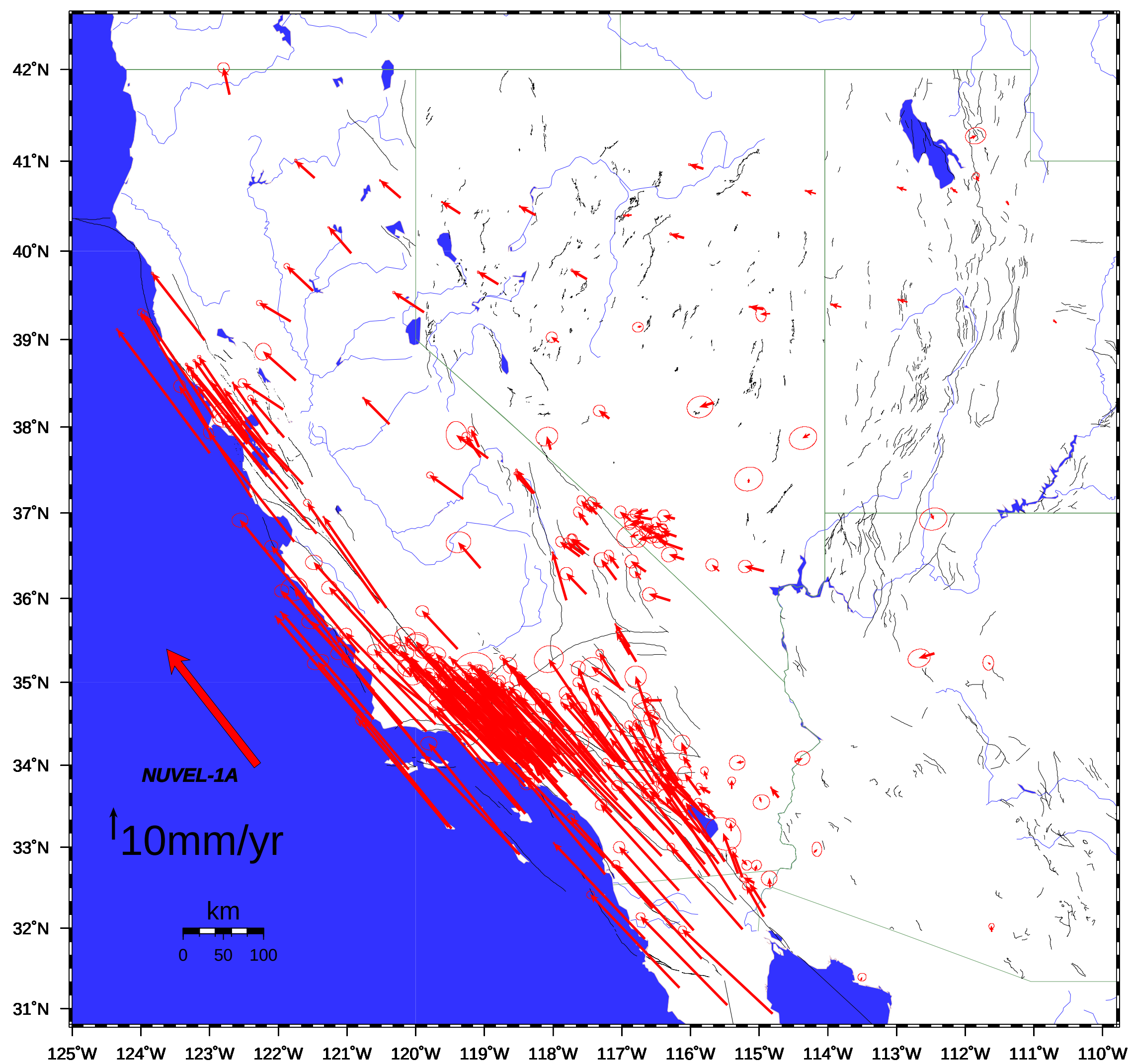

Figure 2 Estimates of horizontal velocities relative to stable North America for sites in western United States (arrows). Error ellipses represent 95‰ confidence level. Thin black lines represent mapped Quaternary faults. Also shown for reference is the NUVEL-1A estimate for Pacific-North America relative motion.